

Automatic Calculation of SUSY-particle Production^{*)}

Masato JIMBO

*Computer Science Laboratory, Tokyo Management College, 625-1 Futamata
Ichikawa, Chiba 272, JAPAN
(e-mail: jimbo@tmc-ipd.ac.jp)*

Hidekazu TANAKA

*Faculty of Science, Rikkyo University, 3-34-1 Nishi-ikebukuro
Toshima, Tokyo 171, JAPAN
(e-mail: tanakah@minami.kek.jp)*

Tadashi KON

*Faculty of Engineering, Seikei University, 3-3-1 Kichijoji-kita
Musashino, Tokyo 180, JAPAN
(e-mail: kon@ge.seikei.ac.jp)*

Toshiaki KANEKO

*Faculty of General Education, Meiji-gakuin University, 1518 Kami-kurata
Totsuka, Yokohama 241, JAPAN
(e-mail: kaneko@minami.kek.jp)*

MINAMI-TATEYA collaboration

Abstract

We introduce a new method to treat Majorana fermions and interactions with fermion-number violation on the GRACE system which has been developed for the automatic computation of the matrix elements for the processes of the standard model. Thus we have constructed a system for the automatic computation of cross-sections for the processes of the minimal SUSY standard model (MSSM).

1 Introduction

At the theoretical point of view, it has been a promising hypothesis that there exists a symmetry called supersymmetry (SUSY) between bosons and fermions at the unification-energy scale. It, however, is a broken symmetry at the electroweak-energy scale. Thus the relic of SUSY is expected to remain as a rich spectrum of SUSY particles, partners of usual matter fermions, gauge bosons and Higgs scalars, named sfermions, gauginos and higgsinos, respectively [1].

The quest of these new particles has already been one of the most important pursuits to the present high-energy physics [2]. Although such particles have not yet been discovered, masses of them are expected to be $O(10^2)$ GeV [3]. In order to obtain signatures of the SUSY-particle production, electron-positron colliding experiments are preferable because the electroweak interactions are clean and well-known. Thus we hope SUSY particles will be detected at future e^-e^+ -colliders of sub-TeV-region or TeV-region energies such as LEP2 or NLC's (Next Linear Colliders) [4, 5].

^{*)}Talk presented by M.Jimbo at Xth International Workshop for HEP and QFT, Zvenigorod, September 1995.

For the simulations of the experiments, we have to calculate the cross-sections for the processes with the final 3-body or more. We have already known within the standard model that the calculation of the helicity amplitudes is more advantageous to such a case than that of the traces for the gamma matrices with **REDUCE** [6, 7]. The program package **CHANEL** [8] is one of the utilities for the numerical calculation of the helicity amplitudes, which has been developing by one of the authors (H.T.).

It, however, is also hard work to construct a program with many subroutine calls of **CHANEL** by hand. Thus we need a more convenient way to carry out such a work. Several groups have started independently to develop computer systems which automate the perturbative calculation in the standard model with different methods [9, 10, 11, 12, 13]. The **GRACE** system [9], which automatically generates the source code for **CHANEL**, is one of the solutions. The system also includes the interface and the library of **CHANEL**, and the program package **BASES/SPRING** v5.1 [14] for multi-dimensional integrations and event-generations.

In the SUSY models, there exist Majorana fermions as the neutral gauginos and higgsinos, which become the mixed states called neutralinos. Since anti-particles of Majorana fermions are themselves, there exists so-called ‘Majorana-flip’, the transition between particle and anti-particle. This is the most important problem which we should solve when we realize the automatic system for computation of the SUSY processes.

In a recent work [15, 16], we developed an algorithm to treat Majorana fermions in **CHANEL**. In the standard model, we already have such particles as Dirac fermions, gauge bosons and scalar bosons in the **GRACE** system. There, however, exists another problem on fermion-number violating interactions. We have also developed an algorithm for this problem. Thus we can construct an automatic system for the computation of the SUSY processes by the algorithms above in the **GRACE** system.

2 SUSY particles and interactions into GRACE 2.0

In Fig. 1, we present the system flow of **GRACE** (after version 1.1) [17]. The **GRACE** system has become more flexible for the extension in the new version called ‘**grc**’ [18], which is written by **C**, and includes a new graph-generation package [19]. With this package, any graphs based on a user-defined model can be generated at any orders. The Feynman diagrams are drawn by the program package ‘**gracefig**’ [20] in the new **GRACE**. It is necessary for us to make the interface and the library of **CHANEL** and the model file for including the SUSY particles.

The method of computation in the program package **CHANEL** is as follows:

1. To divide a helicity amplitude into vertex amplitudes.
2. To calculate each vertex amplitude numerically as a complex number.
3. To reconstruct of them with the polarization sum, and calculate the helicity amplitudes numerically.

The merit of this method is that the extension of the package is easy, and that each vertex can be defined only by the type of concerned particles.

Here we use an algorithm [15, 16] for the implementation of the embedding Majorana fermions in **CHANEL** as follows:

- **policy**

1. To calculate a helicity amplitude numerically.
2. To replace each propagator by wave functions or polarization vectors, and calculate vertex amplitudes.
3. **Not to** move charge-conjugation matrices.

- **method**

1. To choose a direction on a fermion line.
2. To put wave functions, vertices and propagators along the direction in such a way:
 - i) To take the transpose for the reverse direction of fermions

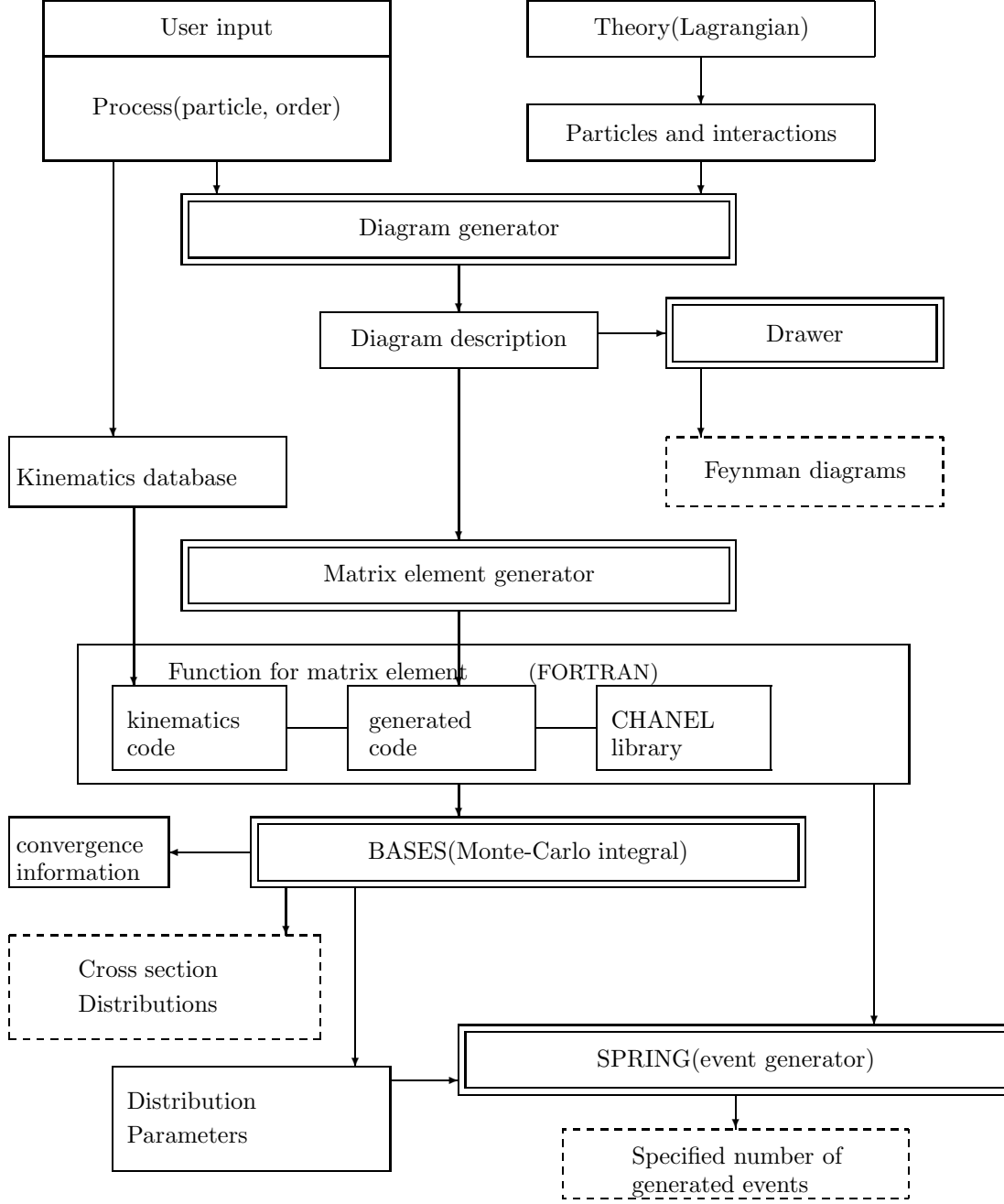


Fig. 1. GRACE system flow (after version 1.1)

- ii) To use the propagator with the charge-conjugation matrix for the Majorana-flipped one.

As a result, the kinds of the Dirac-Majorana-scalar vertices are limited to four types:

$$J_{1\ h_1 h_2}^{[S]\rho_1\rho_2} = \bar{U}^{\rho_1}(h_1, p_1, m_1) \Gamma U^{\rho_2}(h_2, p_2, m_2) \ , \quad (2.1)$$

$$J_{2\ h_1 h_2}^{[S]\rho_1\rho_2} = U^{\rho_1 T}(h_1, p_1, m_1) \Gamma \bar{U}^{\rho_2 T}(h_2, p_2, m_2) \ , \quad (2.2)$$

$$J_{3\ h_1 h_2}^{[S]\rho_1\rho_2} = \bar{U}^{\rho_1}(h_1, p_1, m_1) C^T \Gamma^T \bar{U}^{\rho_2 T}(h_2, p_2, m_2) \ , \quad (2.3)$$

$$J_{4\ h_1 h_2}^{[S]\rho_1\rho_2} = U^{\rho_1 T}(h_1, p_1, m_1) \Gamma^T C^{-1} U^{\rho_2}(h_2, p_2, m_2) \ , \quad (2.4)$$

where U 's denote wave functions, and C is the charge-conjugation matrix. The symbol Γ stands for the scalar vertex such as

$$\Gamma = A_L \cdot \frac{1 - \gamma_5}{2} + A_R \cdot \frac{1 + \gamma_5}{2} \ .$$

The vertices $J_2^{[S]} \sim J_4^{[S]}$ are related to the vertex $J_1^{[S]}$ which has been already defined as the Dirac-Dirac-scalar vertex in the subroutine FFS of CHANEL. The relations among the vertices are as follows:

$$J_{1\ h_1 h_2}^{[S]\rho_1\rho_2} \rightarrow \text{FFS} \ , \quad (2.5)$$

$$J_{2\ h_1 h_2}^{[S]\rho_1\rho_2} = -J_{1\ h_1 h_2}^{[S]-\rho_1-\rho_2} \rightarrow \text{FFST} \ , \quad (2.6)$$

$$J_{3\ h_1 h_2}^{[S]\rho_1\rho_2} = -J_{1\ h_1 h_2}^{[S]\rho_1-\rho_2} \rightarrow \text{FFCS} \ , \quad (2.7)$$

$$J_{4\ h_1 h_2}^{[S]\rho_1\rho_2} = -J_{1\ h_1 h_2}^{[S]-\rho_1\rho_2} \rightarrow \text{FFSC} \ , \quad (2.8)$$

Thus we can build three new subroutines **FFST**, **FFCS** and **FFSC**. We have performed the installation of the subroutines above with the interface on the **GRACE** system version 2.0 [21, 16, 22, 23, 24, 25].

Next we propose an algorithm for the interactions with fermion-number violation such as the chargino-selectron-antineutrino vertex. We introduce two new subroutines [26, 27].

3 Tests for the system

At the first stage for the check of our system, we have written the model file of the SUSY QED. In this case, there is only one Majorana fermion called photino. It is essential for testing our system to include photino and its interactions.

Next we have extended the model file and the definition file of couplings for the MSSM. The tests have been performed by the exact calculations with the two methods, our system and **REDUCE**, in such a manner:

1. To calculate the differential cross-sections at a point of the phase space in the two methods with **GRACE** and **REDUCE**.
2. To calculate the differential cross-sections over the phase space in the two methods with **GRACE** and **REDUCE** through **BASES**.
3. To integrate the differential cross-sections over the phase space in the two methods with **GRACE** and **REDUCE** through **BASES**.

With **BASES**, we can get the differential cross-sections and the scattered plots by one time of the integration step. For writing **REDUCE** sources, we use the different method to treat Majorana fermions in Ref. [13].

In Table I, the tested processes are shown as a list. The references in the table (without [16], [24] and [32]) are not the results of the tests, but for help.

In Ref. [32], we show the angular distribution of the outgoing positron in the process $e^- e^+ \rightarrow \tilde{e}_R^- \tilde{\gamma} e^+$. Here we use **BASES** for the calculation from the **REDUCE** output. The result is in beautiful agreement with the value that is obtained by **GRACE** at each bin of the histogram. Since the two diagrams with the one-photon exchange dominate in this case, there is a steep peak in the direction of the initial positron. In such a case, the equivalent-photon approximation (EPA) works well [31].

Process	Number of diagrams	Comment	Check	Reference
SUSY QED				
$e^-e^- \rightarrow \tilde{e}_R^- \tilde{e}_R^-$	2	Majorana-flip	OK	[16]
$\tilde{e}_L^- \tilde{e}_L^-$	2	in internal lines	OK	[16]
$\tilde{e}_R^- \tilde{e}_L^-$	2		OK	[16]
$e^-e^+ \rightarrow \tilde{e}_R^- \tilde{e}_R^+$	2	Including pair	OK	[23, 28]
$\tilde{e}_L^- \tilde{e}_L^+$	2	annihilation	OK	[23, 28]
$e^-e^+ \rightarrow \tilde{e}_R^- \tilde{e}_L^+$	1	Values are	OK	[23, 28]
$\tilde{e}_R^+ \tilde{e}_L^-$	1	equal	OK	[23, 28]
$e^-e^+ \rightarrow \tilde{\gamma} \tilde{\gamma}$	4	F-B symmetric	OK	[16]
$e^-e^+ \rightarrow \tilde{\gamma} \tilde{\gamma} \gamma$	12	Final 3-body	OK	[29]
$e^-e^+ \rightarrow \tilde{e}_R^- \tilde{\gamma} e^+$	12	Including every elements for tests	OK	[30, 31] [32]
MSSM				
$e^-e^- \rightarrow \tilde{e}_L^- \tilde{e}_L^-$	8	4 Majorana fermions	OK	[24]
$e^-e^+ \rightarrow \tilde{\chi}_1^- \tilde{\chi}_1^+$	3		OK	[24]
$e^-e^+ \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$	14	Final 3-body	OK	[24]

Table I. The list of the tested processes.

4 Summary

We introduce a new method to treat Majorana fermions and interactions with fermion-number violation on the **GRACE** system for the automatic computation of the matrix elements for the processes of the SUSY models. In the first instance, we have constructed the system for the processes of the SUSY QED because we should test our algorithm for the simplest case. Next we have extended the model file and the definition file of couplings for the MSSM. The numerical results convince us that our algorithm is correct.

5 Acknowledgements

This work was supported in part by the Ministry of Education, Science and Culture, Japan under Grant-in-Aid for International Scientific Research Program No.04044158 and No.07044097. Two of the authors (H.T. and M.J.) have been also indebted to the above-mentioned Ministry under Grant-in-Aid for Scientific Research (C) Program No.06640411.

References

- [1] H.P. Nilles, *Phys. Rep.* **110** (1984), 1.
H.E. Haber and G.L. Kane, *Phys. Rep.* **117** (1985), 75.
M. Chen, C. Dionisi, M. Martinez and X. Tata, *Phys. Rep.* **159** (1988), 201.
R. Barbieri, *Riv. Nuovo Cimento* **11** (1988).
R. Barbieri *et al.*, *Z PHYSICS AT LEP 1*, CERN Report *CERN 89-08* Vol.2 (1989), p.121.
- [2] C. Dionisi, in *Proceedings of XVII International Meeting on Fundamental Physics, PHYSICS AT LEP*, Lekeitio, April 23-29, 1989, edited by M.A.-Benítez and M. Cerrada, (World Scientific, Singapore, 1990), p.71.
ALEPH Collaboration, D. Decamp *et al.*, *Phys. Lett.* **244B** (1990), 541.
DELPHI Collaboration, P. Abreu *et al.*, *Phys. Lett.* **247B** (1990), 157.
Proceedings of the Joint International Lepton-Photon Symposium & Europhysics Conference on

High Energy Physics, Geneva, Switzerland, July 25-August 1, 1991, edited by S. Hegarty, K. Potter and E. Quercigh, (World Scientific, Singapore, 1992).

- [3] R. Barbieri and G. Giudice, *Nucl. Phys.* **B296** (1988), 75.
 T. Kon and M. Jimbo, in *Proceedings of the First Workshop on Japan Linear Collider (JLC)*, KEK, October 24-25, 1989, edited by S. Kawabata, *KEK Report 90-2* (1990), p.280.
 M. Jimbo, in *Proceedings of the Second Workshop on Japan Linear Collider (JLC)*, KEK, November 6-8, 1990, edited by S. Kawabata, *KEK Proceedings 91-10* (1991), p.185.
- [4] *Proceedings of the workshop on Physics at Future Accelerators*, La Thuile and CERN, January 1987, edited by J.H. Mulvey, CERN Report *CERN 87-07* (1987).
 C. Ahn *et al.*, *SLAC-Report-329* (1988).
Proceedings of the Third Workshop on Japan Linear Collider (JLC), KEK, February 18-20, 1992, edited by A. Miyamoto, *KEK Proceedings 92-13* (1992).
- [5] H. Bear *et al.*, preprint *FSU-HEP-950401 (LBL-37016, UH-511-822-95 and hep-ph/ 9503479)* (1995), and References therein.
- [6] H. Tanaka, T. Kaneko and Y. Shimizu, *Comput. Phys. Commun.* **64** (1991), 149.
- [7] I. Watanabe, H. Murayama and K. Hagiwara, in *Proceedings of the Third Workshop on Japan Linear Collider (JLC)*, KEK, February 18-20, 1992, edited by A. Miyamoto, *KEK Proceedings 92-13* (1992), p.265.
- [8] H. Tanaka, *Comput. Phys. Commun.* **58** (1990), 153.
- [9] T. Kaneko, in *New Computing Techniques in Physics Research*, edited by D. Perret-Gallix and W. Wojcik, (Édition du CNRS, Paris, 1990), p.555.
 T. Kaneko and H. Tanaka, in *Proceedings of the Second Workshop on Japan Linear Collider (JLC)*, KEK, November 6-8, 1990, edited by S. Kawabata, *KEK Proceedings 91-10* (1991), p.250.
 T. Kaneko, in *New Computing Techniques in Physics Research II*, edited by D. Perret-Gallix, (World Scientific, Singapore, 1992), p.659.
 T. Ishikawa, T. Kaneko, K. Kato, S. Kawabata, Y. Shimizu and H. Tanaka (Minami-Tateya group), *GRACE manual Version 1.0*, *KEK Report 92-19* (1993), and References therein.
- [10] E. Boos, M. Dubinin, V. Edneral, V. Ilyin, A. Kryukov, A. Pukov, V. Savrin, S. Shichanin and A. Taranov, in *New Computing Techniques in Physics Research*, edited by D. Perret-Gallix and W. Wojcik, (Édition du CNRS, Paris, 1990), p.573.
 E. Boos, M. Dubinin, V. Edneral, V. Ilyin, A. Kryukov, A. Pukov, S. Shichanin, in *New Computing Techniques in Physics Research II*, edited by D. Perret-Gallix, (World Scientific, Singapore, 1992), p.665.
 A. Pukov, in *New Computing Techniques in Physics Research III*, edited by K.-H. Becks and D. Perret-Gallix, (World Scientific, Singapore, 1994), p.473.
- [11] J. Küblbeck, M. Böhm and A. Denner, *Comput. Phys. Commun.* **60** (1990), 165.
 R. Mertig, M. Böhm and A. Denner, *Comput. Phys. Commun.* **64** (1991), 345.
 R. Mertig, in *New Computing Techniques in Physics Research III*, edited by K.-H. Becks and D. Perret-Gallix, (World Scientific, Singapore, 1994), p.467.
 H. Eck and J. Küblbeck, *ibid.*, p.565.
- [12] T. Stelzer and W.F. Long, *Comput. Phys. Commun.* **81** (1994), 357.
- [13] A. Denner, H. Eck, O. Hahn and J. Küblbeck, *Phys. Lett.* **B 291** (1992), 278.
 A. Denner, H. Eck, O. Hahn and J. Küblbeck, *Nucl. Phys.* **B 387** (1992), 467.
- [14] S. Kawabata, *Comput. Phys. Commun.* **41** (1986), 127.
 S. Kawabata, *Comput. Phys. Commun.* **88** (1995), 309.

- [15] M. Jimbo and H. Tanaka, *Talk presented at JPS meeting*, Fukuoka, March 28-31, 1994.
- [16] M. Jimbo, H. Tanaka, T. Kaneko, T. Kon and Minami-Tateya collaboration, in *Physics of e^+e^- , $e^-\gamma$ and $\gamma\gamma$ collisions at linear accelerators — Proceedings of the INS Workshop*, INS, December 20-22, 1994, edited by Z. Hioki, *et al.*, **INS-J-181** (1995), p.222.
- [17] Minami-Tateya collaboration, *The document file for GRACE version 1.1*, `kek/minami/grace/grace.tar.Z` at `ftp.kek.jp` (130.87.34.28), (1994).
- [18] T. Kaneko, in *New Computing Techniques in Physics Research IV — Proceedings of the Fourth International Workshop on Software Engineering, Artificial Intelligence and Expert Systems for High Energy and Nuclear Physics (AIHENP95)*, Pisa, Italy, April 3-8, 1995, edited by B. Denby and D. Perret-Gallix, (World Scientific, Singapore, 1995), p.313.
- [19] T. Kaneko, *Comput. Phys. Commun.* **92** (1995), 127.
- [20] T. Ishikawa, S. Kawabata and Y. Kurihara, in *Proceedings of the Fifth Workshop on Japan Linear Collider (JLC)*, Kawatabi, Miyagi, February 16-17, 1995, edited by Y. Kurihara, *KEK Proceedings* **95-11** (1995), p.92.
- [21] T. Ishikawa, S. Kawabata, Y. Kurihara and T. Kaneko, *Brief Manual of Grace System Version 2.0 β* (1995), unpublished.
- [22] M. Jimbo, T. Kon and Minami-Tateya collaboration, in *Proceedings of the YITP Workshop on Particle Physics and its Future Perspective*, YITP, January 17-20, 1995, edited by K. Suehiro, *Soryushiron Kenkyu* **92** (1995), p.31.
- [23] M. Jimbo, in *Proceedings of the Second Workshop on Japan Linear Collider (JLC)*, KEK, November 6-8, 1990, edited by S. Kawabata, *KEK Proceedings* **91-10** (1991), p.185.
- [24] T. Kaneko, H. Tanaka, M. Jimbo, T. Kon and Minami-Tateya collaboration, to appear in *ELECTROWEAK INTERACTIONS AND UNIFIED THEORIES — Proceedings of XXXth Rencontres de Moriond*, Les-Arc, France, March 11-18, 1995.
See also <http://jlcux1.kek.jp/subg/susy/lib/DOC/Grace/grace.html>.
- [25] M. Jimbo, T. Kon, H. Tanaka, T. Kaneko and Minami-Tateya collaboration, in *New Computing Techniques in Physics Research IV — Proceedings of the Fourth International Workshop on Software Engineering, Artificial Intelligence and Expert Systems for High Energy and Nuclear Physics (AIHENP95)*, Pisa, Italy, April 3-8, 1995, edited by B. Denby and D. Perret-Gallix, (World Scientific, Singapore, 1995), p.149.
- [26] H. Tanaka, T. Kon, M. Jimbo, T. Kaneko and Minami-Tateya collaboration, in preparation.
- [27] T. Kon, *Talk presented at Workshop on Physics and Experiments with Linear Colliders*, Morioka-Appi, Iwate, Japan, September 8-12, 1995.
- [28] M. Jimbo, in *Frontiers of High Energy Spin Physics — Proceedings of the 10th International Symposium on High Energy Spin Physics (Yamada Conference XXXV)*, Nagoya, Japan, November 9-14, 1992, edited by T. Hasegawa, N. Horikawa, A. Masaike and S. Sawada, (Universal Academy Press, 1993), p.657.
M. Jimbo, *Memoirs of Tokyo Management College* **I** (1993), 101, and References therein.
- [29] T. Kon, *Prog. Theor. Phys.* **79** (1988), 1006, and References therein.
- [30] M. Jimbo, T. Kon and T. Ochiai, Rikkyo University preprint **RUP-87-1** (1987).
M. Jimbo, *Prog. Theor. Phys.* **79** (1988), 899, and References therein.

- [31] M. Jimbo and M. Katuya, *Europhys. Lett.* **16** (1991), 243.
M. Jimbo and M. Katuya, in *Proceedings of the KEK Summer Institute on High Energy Phenomenology*, KEK, August 21-25, 1990, edited by K. Hikasa, *KEK Proceedings* **91-8** (1991), p.84, and References therein.
- [32] M. Jimbo and Minami-Tateya collaboration, in *Proceedings of the Fifth Workshop on Japan Linear Collider (JLC)*, Kawatabi, Miyagi, February 16-17, 1995, edited by Y. Kurihara, *KEK Proceedings* **95-11** (1995), p.98.